

Integrated wellbore cleaning, near-wellbore stimulation, and water–air injection for restoring productivity and enhancing oil recovery in mature oil fields

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Abstract. Mature oil fields are commonly characterized by declining production rates, increasing water production, formation damage, near-wellbore plugging, sand accumulation, and decreasing efficiency of conventional reservoir-displacement processes. These factors act at different spatial scales, from the wellbore to the near-wellbore zone and the reservoir, and therefore require complementary technological solutions. This paper presents an integrated technological approach based on three complementary developments: a structured washing fluid for sand-plug removal and wellbore restoration; a piston-pump-driven impact-wave device for near-wellbore stimulation; and an ejector system for generating a water–air mixture without an external gas-supply system. The technologies are considered as sequential components of a unified production-restoration and oil-recovery concept. The first technology restores wellbore accessibility by improving the suspension and transport of sand particles. The second restores reservoir-to-well connectivity by generating pressure waves directed toward the perforated productive interval. The third extends the stimulation effect to the reservoir scale by injecting a water–air mixture to improve oil displacement. Laboratory studies associated with the ejector technology demonstrated final oil-displacement factors of 0.50 for formation water, 0.46 for air, and 0.62 for the water–air mixture. A field test of the impact-wave device increased oil production from 0.4 to 1.0 t/day while water production remained at 6 t/day. The washing-fluid technology was implemented in several production wells affected by sand-plug formation; quantitative production indicators are to be incorporated from the original field records. The integrated concept provides a basis for combining wellbore cleaning, near-wellbore stimulation, and reservoir-scale displacement improvement within a unified strategy for mature oil-field development.

Keywords: mature oil fields; wellbore restoration; sand-plug removal; washing fluid; sand transport; near-wellbore stimulation; impact waves; pressure-wave stimulation; ejector; water–air mixture; enhanced oil recovery; residual oil; production intensification.

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1. Aim

The aim of this study is to formulate a unified technological concept for restoring and intensifying oil production in mature fields by combining three complementary levels of intervention: wellbore cleaning, near-wellbore stimulation, and reservoir-scale oil-displacement enhancement.

The specific **objectives** are to:

1. develop a structured washing-fluid approach capable of suspending and transporting sand particles and removing sand plugs;

2. restore reservoir-to-well connectivity using directed impact-wave stimulation;
3. improve reservoir oil displacement by generating and injecting a water–air mixture using the hydraulic energy of injection water;
4. integrate the three technologies into a multiscale production-restoration strategy.

2. Introduction

The development of mature oil fields requires increasingly complex approaches to maintaining production and recovering remaining hydrocarbon reserves. During late-stage field development, production wells may experience declining productivity, increasing water production, sand accumulation, formation damage, and deterioration of reservoir displacement efficiency [1-21].

These restrictions may occur at different spatial levels. Sand accumulation and sand plugs primarily affect the wellbore. Formation damage and plugging can restrict flow in the near-wellbore zone. At the reservoir scale, incomplete sweep and residual oil reduce the effectiveness of conventional water flooding. Consequently, a single stimulation method may not address all dominant production limitations.

The present study therefore proposes a multiscale technological framework:

wellbore → near-wellbore zone → reservoir, (I)

with the corresponding interventions:

sand-plug removal → flow-connectivity restoration → displacement enhancement. (II)

This approach provides the scientific basis for integrating three technologies originally developed as separate engineering solutions [1-8].

3. Integrated Technological Concept

The proposed technological pathway is shown schematically in Figure 1.

The figure emphasizes that the three technologies act at different but interconnected levels of the production system.

The integrated sequence can therefore be represented as:

**Wellbore obstruction → Near-wellbore restriction →
Reservoir displacement limitation (III)**

and:

Cleaning → Stimulation → Enhanced displacement. (IV)

The technologies are not necessarily intended for simultaneous application in every well. Rather, they form a complementary technological portfolio that can be selected according to the dominant production constraint.

4. Technology I – Structured Washing Fluid for Sand-Plug Removal

4.1. Problem and technological concept

Intensive sand production may occur in weakly cemented and unstable formations. Accumulation of sand particles can result in the formation of large sand plugs, restricting wellbore flow and potentially leading to well shutdown.

Conventional washing fluids may not provide sufficient carrying capacity for coarse particles or adequate control of fluid losses. The proposed washing-fluid technology addresses this problem through a structured, high-viscosity and micro-aerated system.

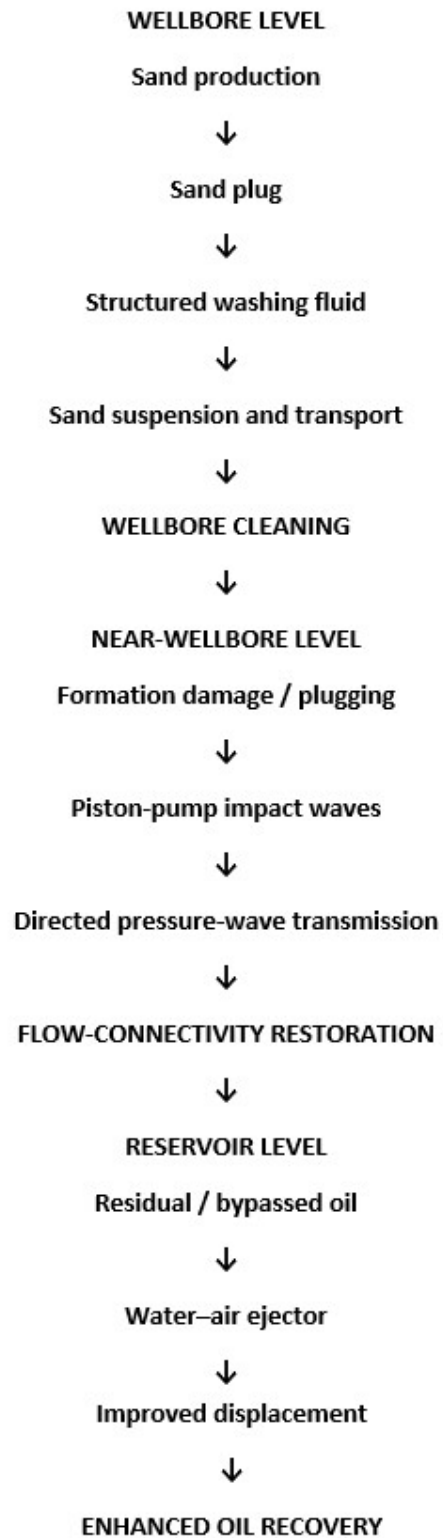


Figure 1. Multiscale technological pathway for restoration and enhancement of oil production in mature fields.

4.2. Composition

The optimal composition of the drilling fluid is given below.

Component wt. %	Concentration,
Quicklime (CaO)	0.5–1.0
Aluminium sulfate	0.5–1.0
Sodium silicate (liquid glass)	0.25–0.50
NIAGARA (AR–FFFP)	0.025–0.05
Technical or seawater	Balance

The functional architecture is:

$CaO + Al_2(SO_4)_3 \rightarrow$ dispersed/colloidal structure + liquid glass $\rightarrow$ structure strengthening + NIAGARA $\rightarrow$ micro-aeration. (V)

The resulting fluid combines structural strength, viscosity, micro-aeration and sand-carrying capacity.

4.3. Sand-transport criterion

An important engineering parameter is the relationship between the upward fluid velocity and the settling velocity of the transported sand particles.

The mean upward fluid velocity is:

$$v_f = \frac{Q}{A}, (1)$$

where Q is the washing-fluid flow rate and A is the effective flow area.

For a simplified particle-settling model, the terminal settling velocity can be estimated as:

$$v_t = \sqrt{\frac{4gd_p(\rho_p - \rho_f)}{3C_D\rho_f}}, (2)$$

where d_p – characteristic particle diameter; ρ_p – particle density; ρ_f – washing-fluid density; C_D – drag coefficient; g – gravitational acceleration.

A useful engineering transport criterion is therefore:

$$\frac{v_f}{v_t} > 1, (3)$$

which indicates that the upward flow velocity is greater than the characteristic settling velocity under the adopted simplified model.

The washing-fluid design is consequently related not only to chemical composition but also to flow velocity, density, viscosity and particle characteristics. In practical applications, the criterion should be evaluated together with the non-Newtonian rheology of the actual washing fluid.

4.4. Mechanism

The treatment sequence is:

washing-fluid injection → contact with sand plug → particle mobilization → suspension → upward transport → sand removal → wellbore restoration. (VI)

The principal controlled parameters include:

- effective viscosity; static shear stress; density; structural stability; mixing intensity; sand-carrying capacity; fluid-loss tendency.

The engineering objective is to maintain sufficient carrying capacity while avoiding excessive hydraulic resistance and undesirable fluid losses.

4.5. Field implementation

The technology was implemented in actual production wells, including wells of “Absheronneft” (781, 403, 1047 and 994), Well 1491 of A. J. Amirov, and Wells 1242 and 1196 of Z. A. Tagiyev.

For Well 1242: depth: 1570 m; filter interval: 1556–1566 m; oil production: 1.3 t/day; water production: 9 t/day; inter-repair period: 30 days.

Based on initial well data, the use of an optimal drilling fluid composition resulted in reduced flushing time and a longer post-treatment interval between workovers, as well as increased sand removal and post-treatment oil production.

5. Technology II – Impact-Wave Stimulation of the Near-Wellbore Zone

5.1. Problem

After removal of a sand plug, production may remain restricted by formation damage or plugging in the near-wellbore zone.

The second technology addresses this limitation through pressure-wave stimulation.

5.2. Device design

Figure 2 shows a schematic of the device for shock-wave treatment of the near-wellbore zone. The device includes:

1. tubing; 2. threaded coupling; 3. connecting pipe; 4. piston pump; 5. bottom support; 6. pipe with outlet openings; 7. outlet openings; 8. support pipe; 9. plug.

The assembly is prepared at the surface, connected by threaded joints and checked for leak tightness.

The main engineering feature is the use of the piston pump as the impact-wave-generating mechanism.

5.3. Operating principle

The device is positioned so that the outlet openings correspond to the perforated productive interval.

Reciprocating piston motion produces pressure fluctuations in the well fluid:

Piston motion → pressure fluctuations → pressure waves → perforations → near-wellbore zone. (VII)

The dynamic action can promote disruption and removal of plugging materials and improve reservoir-to-well flow connectivity.

Compared with the prototype [3] employing pneumatic piston control and multiple valves, the proposed device simplifies the wave-generation mechanism.

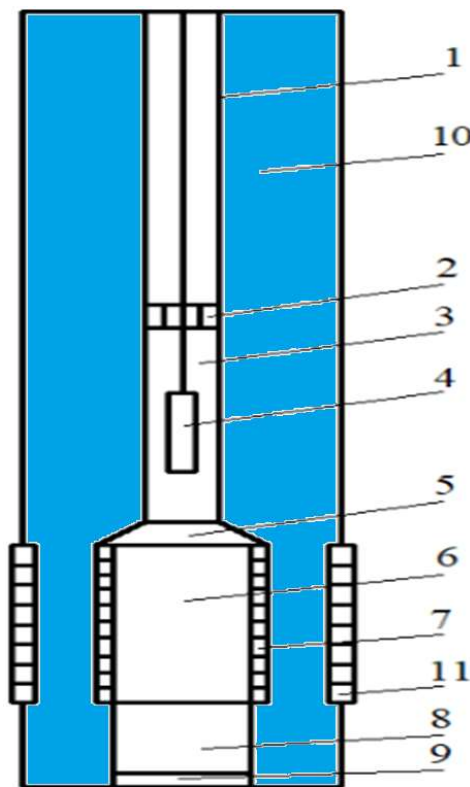


Figure 2. Schematic of the device for shock-wave stimulation of the near-wellbore zone.

5.4. Field test

The device was tested in Production Well No. 1510 at the Gala oil field in Azerbaijan.

Oil production increased from: 0.4 → 1.0 t/day, corresponding to a 2.5-fold increase and an absolute increase of 0.6 t/day.

Water production remained unchanged: 6 → 6 t/day.

The result demonstrates an increase in oil production without a simultaneous increase in water production during the reported test.

6. Technology III – Ejector-Based Water–Air Injection

6.1. Problem

At the reservoir scale, mature fields may contain substantial residual or bypassed oil because of incomplete sweep and declining displacement efficiency.

The third technology addresses this problem by generating a water–air mixture using the hydraulic energy of injection water.

6.2. Ejector design

A schematic diagram of the ejector design is shown in Fig. 3.

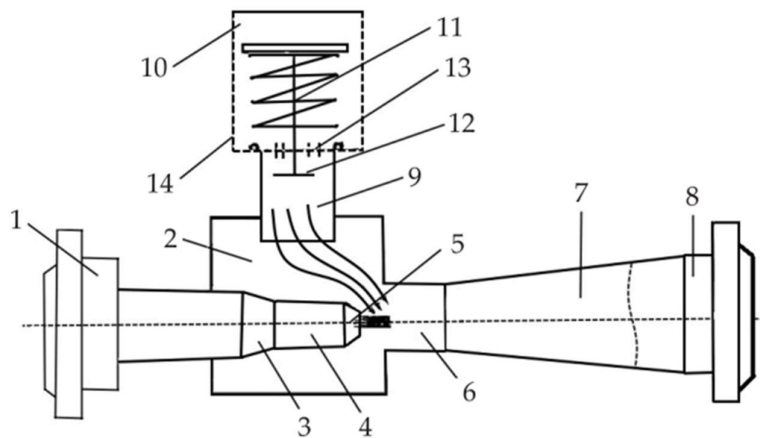


Figure 3. Schematic of the ejector assembly.

The ejector contains: 1. liquid inlet pipe; 2. receiving chamber; 3. confuser; 4. internal liquid pipe; 5. nozzle; 6. mixing chamber; 7. diffuser; 8. outlet pipe; 9. connecting branch pipe; 10. suction chamber; 11. spring; 12. dish-shaped valve; 13. air passage openings; 14. air intake openings.

The principal engineering innovation is the integration of a suction chamber and spring-loaded valve arrangement that enables atmospheric air to be entrained without a separate external gas-supply system.

6.3. Operating principle

The process is:

Pressurized water → velocity increase → pressure reduction → air suction → water–air mixing. (VIII)

The resulting mixture is delivered to the injection well and subsequently to the reservoir.

The ejection ratio is defined as:

$$R = \frac{V_{air}}{V_{water}}, (4)$$

where V_{air} is the air volume and V_{water} is the water volume.

The reported optimum regime corresponded to approximately 60% air in the total mixture volume.

6.4. Laboratory results

Linear reservoir models had a length of 1.2 m and an internal diameter of 0.026 m. Quartz sand of different fractions with clay was used to reproduce heterogeneity. Initial model saturation consisted of 80% oil and 20% residual water.

Working agent	Final oil-displacement factor
Formation water	0.50
Air	0.46
Water + air	0.62

The water–air mixture produced the highest final oil-displacement factor.

6.5. Field test

The ejector was tested at Production Well No. 1781 in the second area of Siyəzənneft and connected to Injection Well No. 349.

Before the test:

- oil production: 8 t/month;
- produced water: 174 m³/month.

After seven months:

- additional oil production: 130 t;
- produced water: 90 m³/month.

These results indicate the potential of the water–air injection approach for mature reservoirs with declining oil production and substantial water production.

7. Integrated Discussion

The three technologies address different production restrictions:

Scale	Main restriction	Technology	Main function
Wellbore	Sand plug	Structured washing fluid	Cleaning and sand transport
Near-wellbore	Formation damage / plugging	Impact-wave device	Connectivity restoration
Reservoir	Residual / bypassed oil	Water–air ejector	Displacement enhancement

This creates the central technological chain:

Wellbore cleaning → Near-wellbore stimulation → Reservoir displacement enhancement. (IX)

The technologies are complementary rather than redundant.

A well dominated by sand plugging may first require washing-fluid treatment. If productivity remains low after cleaning, near-wellbore stimulation may be considered. If wellbore and near-wellbore restrictions are adequately controlled but reservoir-scale displacement remains limiting, water–air injection may be considered.

Thus, the integrated concept provides a diagnostic and intervention framework rather than requiring universal simultaneous application.

8. Scientific Novelty

The scientific novelty of the present study lies in formulating three independent engineering developments as a unified multiscale production-restoration and oil-recovery system.

The novelty consists of:

1. establishing a spatial hierarchy connecting wellbore cleaning, near-wellbore stimulation and reservoir displacement enhancement;
2. connecting rheological sand transport, dynamic pressure-wave stimulation and water–air displacement within one production-restoration framework;
3. extending the conventional concept of well stimulation from a local intervention toward a multiscale wellbore–reservoir strategy;
4. providing a decision-oriented sequence for selecting technological intervention according to the dominant production constraint.

The novelty of the manuscript therefore concerns the integration and scientific interpretation of the three technologies, rather than claiming that each individual technology was invented within the present paper.

9. Practical Significance

The integrated technology portfolio can provide practical benefits at different stages of mature-field operation.

The washing-fluid technology can facilitate sand-plug removal and wellbore restoration.

The impact-wave device can provide a comparatively simple means of stimulating the near-wellbore zone.

The ejector can generate a water–air working mixture using the hydraulic energy of injection water, potentially reducing dependence on an external gas-supply system.

The combined approach may therefore contribute to:

- restoration of wellbore accessibility;
- improved near-wellbore filtration;
- increased oil inflow;
- maintenance or reduction of water production in appropriate cases;
- improved reservoir displacement;
- mobilization of residual oil;
- extension of productive well life;
- reduction of repeated intervention requirements.

The recommended operational strategy is:

Diagnose → Clean → Stimulate → Evaluate → Intensify → Monitor. (X)

10. Conclusions

A unified multiscale technological concept has been developed by combining structured washing-fluid treatment, piston-pump-driven impact-wave stimulation and ejector-based water–air injection.

The principal conclusions are:

1. The structured washing fluid addresses wellbore obstruction by improving sand suspension and transport and facilitating sand-plug removal.
2. The proposed impact-wave device addresses near-wellbore restrictions by generating pressure waves with a piston pump and directing them toward the perforated productive interval.
3. Field testing of the impact-wave device increased oil production from 0.4 to 1.0 t/day, corresponding to a 2.5-fold increase, while water production remained at 6 t/day.
4. The ejector converts hydraulic energy of injected water into an air-entrainment mechanism, enabling formation of a water–air mixture without a separate external gas-supply system.
5. Laboratory reservoir-model experiments produced a final oil-displacement factor of 0.62 for the water–air mixture compared with 0.50 for formation water and 0.46 for air.
6. The three technologies form a spatially hierarchical intervention pathway:

wellbore cleaning → near-wellbore stimulation → reservoir displacement enhancement.

7. The proposed concept is intended as a flexible technology-selection framework in which the intervention is matched to the dominant production limitation.

The resulting approach transforms three separate engineering developments into a coherent pathway from wellbore restoration to near-wellbore stimulation and finally to reservoir-scale oil-recovery enhancement.

Conflict of interest.

The authors declare that they have no conflict of interest in relation to this research.

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